

TENSILE BOND STRENGTH OF STAINLESS STEEL
ORTHODONTIC BRACKETS ON
MICROABRADED TEETH

by

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TABLE OF CONTENTS

Introduction	1
Review of Literature	4
Methods and Materials	27
Results	31
Figures and Tables	33
Discussion	41
Summary and Conclusions	45
References	47
Abstract	58
Curriculum Vitae	

LIST OF ILLUSTRATIONS

FIGURE 1	Specimen in lathe.....	34
FIGURE 2	Specimen with metal bracket bonded to enamel surface.....	35
FIGURE 3	Stress-breaking apparatus to support specimen.....	36
FIGURE 4	Stress-breaking apparatus supporting specimen in the Instron testing machine.....	37
FIGURE 5	Mean tensile bond strength.....	38
FIGURE 6	SEM (X20) of bond failure at the bracket- adhesive interface.....	39
TABLE I	Mean tensile bond strength with spontaneous debonds and fractures excluded.....	40

INTRODUCTION

Direct bonding of orthodontic attachments has become a common technique in orthodontics. Several variables that could influence enamel bonding such as acid etching times,¹⁻³ concentration of acid,^{4,5} type of adhesive,^{6,7} bracket base,⁸ fluoride concentration in the etchant and adhesive,⁹⁻¹¹ and mechanical pretreatments¹²⁻¹⁵ have been investigated.

Enamel fluorosis is becoming more widespread due to communal fluoridation, fluoride in toothpastes, vitamins, and professional fluoride treatments.¹⁶ Investigations to determine the effect that enamel fluorosis has on the tensile bond strength of orthodontic attachments to fluorotic teeth are limited. Also scarce in the literature is the bond strength of brackets bonded to teeth previously treated for enamel stains.

Enamel surfaces disturbed during amelogenesis as a result of (1) local infection, (2) trauma, (3) excessive fluoride consumption, (4) fever, or (5) dehydration can result in brown, white or yellow enamel stains and are considered enamel hypoplasias. In these hypoplasias, the organic matrix deposited by the ameloblast is unorganized and consists of imperfect enamel globules rather than oriented enamel prisms.¹⁷ Various techniques have been described in the literature to remove superficial enamel stains. In 1916¹⁸ Walter Kane used muriatic acid and heat to eliminate brown fluorosis stains. In 1942¹⁹ Younger reported the successful use of a bleaching solution of 5 cc of 30-percent superoxal and 1-cc anesthetic ether in combination with a heated instrument. McInnes²⁰ in 1966 developed a method that included the use of 30-percent superoxal, muriatic acid and anesthetic ether. This formula eliminated enamel discoloration, but modifications of the technique such as the addition of

mechanical abrasion with sand paper disks were reported. McCloskey in 1984¹⁸ described a method using 18-percent hydrochloric acid and pumice. This method was successful in removing enamel stains after a one-time application. In 1989 Croll²¹ reported the use of a new method of treatment that he referred to as "enamel microabrasion." This new method used a gel-like acid material (PREMA Compound, Premier Dental Product Co., King of Prussia, Penn.), that contains a mild concentration of hydrochloric acid and a fine-grit silicon carbide abrasive in a water-soluble gel. The PREMA treatment is not a bleaching technique but a uniform mechanical and chemical removal (about 50 to 150 μm) of enamel.

Patients in the mixed dentition could have superficial enamel discolorations and a need for orthodontic treatment. Because of the psychological ramifications of enamel discoloration, elimination of the stains could prevent unnecessary psychological scarring. The effect of enamel microabrasion on the bond strength of orthodontic brackets could be of clinical significance to the orthodontist. The purposes of this investigation were to determine if enamel microabrasion using PREMA Compound would have a significant effect on the tensile bond strength of metal orthodontic brackets, and to identify the site of bond failure indicating an adhesive or cohesive failure.

The null hypothesis to be tested in this study was that no significant difference existed among the tensile bond strengths of brackets bonded immediately after PREMA microabrasion, of brackets bonded after a six-week storage period following PREMA microabrasion, and of those bonded in the usual manner.

REVIEW OF LITERATURE

Biomaterials research in orthodontics has addressed the improvement of the mechanical, physical and chemical properties of orthodontic appliances. The improvements have enabled the orthodontist to simplify technical procedures and still achieve the objective. Currently, orthodontic brackets are attached to teeth via adhesives. To better understand this method, a review of the principles of adhesion is presented.

ADHESION AND BONDING

Adhesion is defined as the molecular attraction exerted between the surfaces of bodies in contact or the attraction between molecules at an interface.²² The attractive forces involved in adhesion may be divided into physical and chemical forces. Physical forces include Van der Waal's and those resulting from hydrogen bonds. Chemical forces are stronger and include covalent and electrovalent bonds.²³

Forces responsible for adhesion act over a short distance of separation. Adhesion can occur spontaneously between surfaces that are flat at an atomic level if the surfaces are brought into contact. When it is not possible to obtain such contacting surfaces, a liquid adhesive must be introduced between the solid surfaces to achieve adhesion.²⁴ The liquid adhesive flows between the surfaces and produces the molecular closeness necessary for adhesion.

Wetting is a physical condition of strong attractive forces between the molecules of the liquid adhesive and the adherend or material to which the adhesive is applied.²⁵ Liquids that readily flow into irregularities of a surface exhibit good wetting. The contact angle between the adhesive and the adherend measures the degree of wetting. A small contact angle between the adhesive and

adherend indicates good wetting and strong adhesive forces.²⁵ The contact angle reflects a relation between the surface tension of the liquid adhesive and the solid adherend. The surface tension or surface free energy of the adhesive must be less than the surface tension of the adherend for wetting to occur. The viscosity of the liquid adhesive and the surface of the adherend also influence wetting. A thick adhesive cannot flow easily into the irregularities in the adherend. A fluid or semiviscous liquid adhesive is best suited for penetration into irregularities in the adherend surface.²⁶

Solidification of the adhesive is desirable to maintain the achieved molecular closeness and to give adhesive bulk strength. This can be accomplished by using an adhesive with a volatile component and that sets when the component evaporates, or by using a liquid adhesive, the molecules of which can be made to polymerize or cross-link with each other through the use of catalysts, reactive hardeners, or heat.²²

According to Retief et al.²² an ideal dental adhesive should: set rapidly at or near body temperature with little or no shrinkage; provide a long-lasting bond with enamel and dentin; be sufficiently cross-linked to minimize water absorption; have a coefficient of thermal expansion that approximates that of tooth structure; have sufficient strength to resist forces acting on it; be innocuous to the pulp and oral tissues, and resist degradation in the oral environment.

HISTORY OF ORTHODONTIC BONDING

The technique of cementing orthodontic bands to teeth was introduced by Magil in 1871 and remained the treatment of choice for over 85 years.²⁷ Direct bonding of brackets has replaced banding of anterior teeth and offers significant advantages such as: improved esthetics, ease of placement, patient comfort, elimination of the need for tooth separation, decreased soft tissue irritation,

enhanced detection of interproximal decay, and fewer decalcification spots.²⁸

Newman²⁹ in 1965 was the first to apply an acid-etch technique to the direct bonding of orthodontic attachments. Epoxy resin was used to bond the appliances after a 60-second phosphoric acid etch. Because the setting time of the epoxy resin was so long, Newman's technique did not prove to be clinically useful. Mitchell in 1967³⁰ compared epoxy-polyamide resin and black copper cement and found both unable to maintain their bond integrity in a moist environment. Zinc polycarboxylated cement, introduced by Smith³¹ in 1968, proved to be an effective bonding material. This material was later found to be weak in tension, and clinical failures were reported.³² Newman et al.³³⁻³⁵ described the use of acrylic resins to bond plastic brackets. In the mid-1970s diacrylate resins increased in popularity.³⁴ These adhesives are based on a resin, bisphenol A glycidyl dimethacrylate (Bis-GMA), which was developed by Bowen in 1962. Since the late 1970s, third-generation composite resins have been utilized in orthodontic bonding. The incorporated quartz, glass or silica fillers reduce polymerization shrinkage and the coefficient of thermal expansion and increase the strength and hardness of the composite.³⁶

Since Newman's development of the direct bonding technique, several variables that could alter bond strength of brackets to enamel have been investigated. Some of these include types of acid etchants,^{37,38} concentration of acid,^{4,5} etching time,¹⁻³ fluoride incorporated into the etchant or the adhesive,^{9,11} type of adhesive,^{6,7} bracket base,⁸ enamel surface pretreatments,¹²⁻¹⁵ fluorotic versus nonfluorotic teeth,^{39,40} and bleaching solutions.⁴¹⁻⁴³

ACID ETCHING

Buonocore⁴⁴ in 1955 was the first to demonstrate the effectiveness of acid etching in improving bond to enamel. He compared 85-percent phosphoric acid and a 50-percent phosphomolybdate-10-percent oxalic acid solution for acid etching effectiveness. Phosphoric acid gave higher bond strengths and was simpler to use. Buonocore believed that the improved bond could have been due to such factors as an increase in the surface area of the adherend, exposure of the organic framework of enamel that serves as a network for acrylic adherence, formation of a new surface due to precipitation of substances to which acrylic might adhere, removal of the fully reacted inert enamel surface, or the presence on the enamel surface of an adsorbed layer of highly polar phosphate groups derived from the acid.

Buonocore, Matsui, and Gwinnett⁴⁵ examined the penetration of several resin dental materials into enamel surfaces. Prism-like tags projected from all resin interfaces that had been in contact with conditioned enamel surfaces. Similar tags were not observed where the resin had contacted unconditioned enamel. Buonocore and associates concluded that mechanical retention plays an important role in the bonding of many adhesives to treated enamel surfaces. Etching of enamel opens up interprismatic spaces into which the adhesive can flow and ultimately polymerize.

The use of various acids at different concentrations and exposure times has been investigated. Galil et al.⁴⁶ compared the etching ability of four different acids, phosphoric, pyruvic, lactic, and citric, with differing concentrations and application times. The pyruvic, lactic, and citric acids displayed etching patterns considerably inferior to those obtained by phosphoric acid. Optimal phosphoric acid concentration was found to be in the 30 to 40 percent range with an application time of one to one-and-a-half minutes.

Polyacrylic acid crystal growth has been suggested as an alternative to the conventional phosphoric acid-etch technique. Reported advantages of the crystal technique include: (1) minimal damage to the enamel surface, (2) easier debonding cleanup, (3) minimal loss of the fluoride-rich outer layer of enamel, and (4) few if any resin tags left in the enamel after debonding.⁴⁷ In an *in vitro* study, Maijer and Smith⁴⁷ reported that the polyacrylic acid-formed crystals produced bond strengths comparable to those of the conventional phosphoric acid etch.

Farquhar⁴⁸ compared the shear bond strength of polyacrylic acid and phosphoric acid *in vitro*. The results indicated the mean shear bond for the phosphoric acid group (20.6 Kg) was significantly greater than the polyacrylic acid group (7.7 Kg).

Maskeroni et al.⁴⁹ compared the shear bond strength of metal and ceramic brackets with three enamel preparations: 37-percent phosphoric acid, sulfated polyacrylic acid etch with removal of crystals by rinsing, and polyacrylic acid etch with crystal growth. The polyacrylic crystal growth reduced the strength of the bond to enamel by 50 percent when ceramic brackets were used. This decrease in bond strength reduced the force required to debond ceramic brackets and could have reduced the chance of enamel fracture at debonding.

Mulholland et al.³⁷ explored the effects of acidic pretreatment solutions with varying pH and molarity on direct orthodontic bonding. Two monovalent (hydrofluoric and hydrochloric) and two polyvalent (phosphoric and aspartic) acids were evaluated. A definite correlation was shown between an increase in bond strength and a decrease in pH in the monovalent acids. The polyvalent acids did not show a considerable change in bond strength until a pH of 2 was achieved.

Thornton et al.⁵⁰ evaluated the effect of various fluoride concentrations added to 50-percent phosphoric acid. The results of this study indicated that neither the degree of etch nor bond strength was reduced by the presence of fluoride.

CONCENTRATION OF ACID ETCHANT

Extensive research has been conducted to determine the optimum concentration of etching agents. Soetopo et al.⁵¹ measured the tensile bond strengths after etching with 2- to 60-percent phosphoric acid solutions and reported that 16-percent acid resulted in the highest bond strength with similar values recorded for 2-percent and 40-percent solutions. Gottlieb et al.⁵² determined no significant differences among the tensile bond strengths after etching with 10 to 60 percent phosphoric acid solutions. Zidan and Hill⁵³ also found no significant difference in tensile bond strength after one minute application of 2-percent, 5-percent and 35-percent phosphoric acid solutions. Studies by Barkmeier et al.⁵⁴ and Bryant et al.⁵⁵ also have shown that a phosphoric acid concentration of 5 percent is probably appropriate to achieve sufficient bond strength. Carstensen⁴ in a one-year retrospective study evaluated the clinical results of brackets bonded to anterior teeth utilizing a 2-percent or 37-percent acid etch. No significant difference in failure rates was recorded; however, higher amounts of residual adhesive were seen on those teeth etched with 37-percent phosphoric acid.

ADHESIVES

Several types of adhesives have been evaluated in the dental literature to identify the "ideal" adhesive. Those investigated include: acrylic resins, diacrylate resins, polycarboxylate cements, and glass ionomer cements.

In the 1940s acrylic resins based on self-curing acrylics were introduced to the US dental profession.²⁵ These resins consisted of methyl methacrylate monomer that forms linear polymers. These resins did not prove to be beneficial as restorative resins due to the failure to bond to tooth structure successfully, considerable polymerization shrinkage, and discoloration with exposure in the oral cavity.⁵⁶⁻⁵⁹

Newman²⁹ in the 1960s bonded plastic orthodontic attachments with epoxy resins; however, complete cure of the resin took four days and was impractical for clinical use in orthodontics. Miura et al.⁶⁰ described an acrylic that used a tri-n-borane derivative instead of an amine-peroxide curing system because of the advantage of polymerization in a moist environment.

Currently, most adhesives used in orthodontics are the diacrylate resins based on bisphenol A glycidyl dimethacrylate (Bis GMA).⁶¹ Bis GMA was developed by Bowen in 1962 and was found to have greater strength, lower water sorption, and less polymerization shrinkage.²⁵

In 1972 ultra-violet (UV) light-activated pit and fissure sealant developed by Buonocore was used to bond plastic orthodontic brackets. Cohl et al.⁶² in an *in vitro* study tested the shear and tensile bond strengths at 24 hours and at 30 days and found both to be clinically acceptable. This technique proved to have clinical orthodontic potential because (1) the esthetic results surpassed the use of orthodontic bands, (2) the adhesive polymerized rapidly, and (3) orthodontic forces could be applied immediately.

Garn⁶³ evaluated the clinical effectiveness of UV-activated adhesives with 124 metal and 73 plastic brackets over a seven-month period. A high success rate was found, with metal brackets maintaining their bond 95 percent of the time and resin brackets 89 percent of the time.

Lee et al.⁶⁴ compared UV curing and self-curing materials for preventive, restorative and orthodontic dentistry. UV curing was found to be advantageous due to an increased working time and reduced mixing time. Disadvantages of the UV curing material were also noted. These disadvantages included lack of a uniform cure, discoloration, and harmful effects of UV radiation exposure. Read⁶⁵ also addressed disadvantages of the UV system and recognized that UV light is poorly transmitted by tooth substance, and that a time-consuming 90-second cure is necessary for each bracket. Because of the number of disadvantages with the UV technique, alternative methods of curing were investigated.

A visible light-activated composite resin was evaluated *in vitro* by Tavas and Watts.⁶⁶ Although not clinically optimal, their results introduced the potential of visible light-cured resins for orthodontic bonding.

The visible light-cured resins contain photo initiators that absorb light in the 450 to 500 nanometer range.⁶⁷ The depth of cure for visible light-activated systems surpasses that of the UV light-activated systems.^{68,69} The depth of cure of the visible light-cured resin is dependent on the physical make up of the resin. The smaller and more numerous the particle size of the filler, the greater the light dispersion produced.^{70,71} Visible light activated resins have several clinical advantages such as: no mixing, optimal working time, and a safe spectrum of light for initiation.

The shear bond strengths of an autopolymerizing composite resin and a light-cured microfilled resin were compared by Andreasen et al.⁷¹ Results indicated that after a 40-second cure, no statistically significant difference was found. Tavas and Watts,⁷² utilizing metal brackets, found results similar to Andreasen when comparing chemical and visible light-activated resins.

Leung et al.⁷³ compared polymerization after light activation and found a direct correlation between increased exposure time and hardness value. Tavas and Watts⁷² reported similar findings with an increase in bond strength continuous from 5 to 24 hours after the initial cure.

BRACKET DESIGN

Bond strengths of brackets to enamel could be affected by bracket design and material. Orthodontic bracket materials have included plastic, metal, and ceramic. Plastic brackets achieve high bond strength through molecular attraction with resin adhesives, but the bond can be erratic; the attachments themselves demonstrate low strength and rigidity.⁶ Ceramic brackets bond to resin via mechanical and chemical bonding. Ceramic brackets are brittle and fracture easily, and because of their hardness, they can damage enamel on opposing teeth.^{74,75} Metal brackets have had great acceptance and are more reliable. Perforated bracket bases were replaced by mesh bases and have been found to give stronger bonds and retain less plaque.⁷⁶ The optimal mesh size is still controversial. Majer and Smith⁷⁷ reported that fine mesh bases had the highest bond strength, while Reynold and Von Fraunhofer⁷⁸ found coarse mesh to be the most retentive.

MECHANICAL PRETREATMENTS

Mechanical pretreatment procedures have been studied to determine if there is a significant effect on the etching pattern.¹²⁻¹⁵ Khadry¹² indicated that pretreatment by grinding, or removal of the surface enamel prior to etching, produces a more favorable etch pattern. Brannstrom et al.,¹³ however, found little change in the etch pattern in teeth subjected to grinding with a diamond point or aluminum oxide disc prior to etching, compared with those without prior grinding.

Mechanical pretreatments have also been evaluated for effect on stain removal and bond strength. Barnes et al.¹⁴ advocated air powder polishing as an effective method of eliminating stains and plaque on tooth surface. Gerbo et al.¹⁵ compared the tensile bond strength of brackets when the enamel was cleaned with an air-powder polisher rather than a rubber cup and pumice prior to etching and found no statistical difference in tensile bond strength. Opinya⁴⁰ tested the tensile bond strength of fluorosed and nonfluorosed Kenyan teeth. He found an increase in the bond strength to fluorosed teeth subjected to grinding and polishing with a green stone followed by pumice grinding prior to acid etching.

Microabrasion is another form of enamel pretreatment that effectively removes enamel stains. This technique is particularly advocated for stains associated with dental fluorosis. Dental fluorosis and fluoride have a history in the dental literature that dates back to the 19th century.

FLUORIDE

The discovery and utilization of fluoride in dentistry has had a great impact on dental health. The inverse relationship between fluoride levels and dental caries dates back to the 19th century with Hempel and Scheffler reporting a difference in fluoride content between carious and noncarious teeth.⁷⁹

Systemic fluoride therapy refers to the use of ingested fluoride during the period of tooth formation. The most common and efficient means of providing systemic fluoride is by communal water fluoridation. Fluoride was first added to public drinking water in the 1940s to prevent tooth decay.¹⁶ With the implementation of communal fluoridation, a 60-percent reduction in caries scores was seen in those living in water-fluoridated areas.¹⁶

Four classic studies confirmed the beneficial influence of water fluoridation upon dental caries reduction. These studies are identified by the names of the cities which were involved: Grand Rapids-Muskegon, Mich.; Brantford-Stratford-Sarnia, Ontario; Newburgh-Kingston, N.Y.; and Evanston, Ill.⁷⁹

Studies reveal lower caries scores in naturally or adjusted fluoridated areas. The differences in caries scores between fluoridated and nonfluoridated areas are not as great as those observed in the 1940s. This change could be explained by fluoride consumption through other vehicles such as beverages, food, dental products, and dietary supplements.⁷⁹

HISTORY OF FLUOROSIS

In 1888 Kuhns reported discolored and disfigured teeth of persons in areas of Mexico. In 1901 Eager, while an assistant surgeon of the US Marine Hospital, screened Italian emigrants preparing to leave Naples and noticed a disfiguring condition in their teeth. Upon further investigation he observed that the enamel defect was restricted to persons residing in that area since childhood. Eager termed the condition "denti neri" and believed it to be acquired and caused by local geographic conditions.⁸⁰

In 1908 Frederick S. McKay, a dentist in Colorado Springs, observed a brown stain in some of his patients and coined the term "Colorado Brown Stain." McKay noted that those individuals living in certain locations since their childhood were afflicted with the stain, while those coming to the area as adults did not have the condition. With this information, McKay attributed "brown stain" to a local or geographic factor that occurred during childhood. In 1916 McKay, in collaboration with G. V. Black, introduced this dental anomaly to the dental literature and described it as "mottled enamel." Black and McKay became

interested in determining the causative agent of this disfigurement, and via surveys on the prevalence of the condition, hypothesized that the causative agent was in the drinking water.⁸¹

Churchill⁸² in 1931 reported the presence of fluoride in several water samples from endemic fluorosis areas, but he did not find a correlation between mottled enamel and the water fluoride content. McKay,⁸³ however, believed there was a positive correlation between the fluoride content of drinking water and mottled enamel.

Smith, Lantz, and Smith⁸⁴ also in 1931 showed conclusively that fluoride caused mottled enamel in rats that drank the fluoride-concentrated water found in St. David, Ariz. Previous investigators⁸⁵⁻⁸⁷ had concluded that sodium fluoride fed to experimental animals caused defects in the teeth identical to the mottling seen in humans.

In 1933 Dean⁸⁸ was instrumental in reporting epidemiologic surveys of mottled enamel. He also developed a classification system and reported on the association of fluoride in the water supply with dental caries reductions.⁸⁹

Arnold⁹⁰ reported that the maximum protection against dental caries with the least incidence of endemic dental fluorosis occurred when drinking water containing 0.8 to 1.2 ppm F was ingested during the first 12 years of life.

Today "mottled enamel" is known as chronic endemic dental fluorosis. Dental fluorosis is considered to be one of a number of enamel hypoplasias. Other conditions resulting in enamel hypoplasia include nutritional deficiencies, exanthematous diseases, congenital syphilis, hypocalcemia, birth injury, local infection, trauma, and idiopathic factors.¹⁷

Enamel hypoplasias occur due to factors that interfere with the function of the ameloblast during enamel formation. The organic matrix deposited by the ameloblast is unorganized and consists of imperfect enamel globules rather than

oriented enamel prisms. The extent of chronic endemic dental fluorosis ranges from mild to severe. In the mildest form, the defect consists of white flecking or spotting of the enamel. With an increase in severity, the appearance can range from extensive enamel opacities to pitting and brown stains.¹⁷

MICROABRASION

Enamel microabrasion, somewhat analogous to dermabrasion on skin surfaces, is a procedure in which a microscopic layer of enamel is simultaneously eroded and abraded.⁹¹ Microabrasion by controlled 18-percent hydrochloric acid and pumice is not a new technique but spans back to the early part of the 20th century. According to McCloskey,¹⁸ the first person known to experiment with various acids to reduce unsightly enamel stains was Dr. Walter Kane. Dr. Kane set out to improve the tooth color of those with "Colorado Brown Stain." Dr. Theodore P. Croll in 1986⁹¹ published a pictorial essay describing a technique that had been proven effective for the removal of brown fluorosis stains and many other superficial enamel coloration defects. This technique consisted of using an 18-percent solution of hydrochloric acid and pumice and abrading the affected tooth surface with a wooden tongue blade segment. Croll's technique was successful in eliminating superficial enamel discolorations; however, research continued to improve the enamel microabrasion compound, so that it would be safer and easier to use. A safe enamel microabrasion compound was developed, patented and introduced to the profession in 1990. This compound, PREMA, can be used to eliminate superficial white or yellow stains caused by fluorosis, past trauma, decalcification due to accumulation of bacterial acids, and spots of unknown origin. The benefit of PREMA is that it is safe, inexpensive, and that it offers immediate and permanent results without significant tooth-structure removal or detectable pulpal damage. To date, little is known with

regard to the bond strength of orthodontic brackets on teeth that have been previously microabraded with PREMA Compound. Croll has stated that in the six months following PREMA microabrasion, the enamel surface undergoes remineralization and attains a smooth, glass-like surface.⁹² It has also been suggested by Croll that teeth microabraded with PREMA, or any hydrochloric acid and pumice solution show suboptimal etching patterns after a 30-second etch and could require an additional 15 to 30 seconds prior to orthodontic bracket placement. Studies are still needed to determine if this enamel surface change has any effect on orthodontic bracket bonding, and if a longer etching time is actually necessary.

BLEACHING AND BOND STRENGTH

Vital bleaching of teeth has become a popular treatment modality to combat enamel discoloration. Although in-office bleaching dates to 1918, new and improved techniques continue to be utilized.⁹³ Many studies have addressed the effect on the bond strength of composite to bleached enamel.

Wolff et al.⁹³ evaluated the effect of 10-percent carbamide peroxide on the shear bond strength of orthodontic brackets to extracted premolar teeth. The results indicated that carbamide peroxide gel could cause a weaker bond strength.

Titely et al.⁹⁴ tested the shear bond strength of microfil resin to bovine enamel treated with 10-percent carbamide peroxide bleach and varied the pH from 4.7 to 7.2 and the immersion time from three to six hours. The analysis showed that exposure of the enamel to 10-percent carbamide peroxide for a period of three to six hours resulted in a statistically significant reduction in bond strength. The effect of duration of carbamide peroxide and pH value were not statistically significant. Placing the peroxide-treated enamel in water for either

one or seven days prior to the resin application restored the adhesiveness of the enamel. The reduction in the adhesiveness of the carbamide peroxide treated enamel was thought to be due to the resin-peroxide interaction that occurred at the resin-enamel interface. Scanning electron microscopy (SEM) analysis revealed the presence of a granular, more porous resin at the base of the adhesive. This appearance was gaseous bubbling resulting from entrapment of peroxide in the subsurface layer of the enamel. Elimination of the entrapped peroxide was seen when specimens were leached in water, which resulted in an enamel surface with increased adhesiveness.

Torneck et al.⁹⁵ evaluated the tensile and shear bond strength of resin to bovine enamel immersed in hydrogen peroxide for five or 30 minutes and found a significant reduction in bond strength with increased exposure time. Torneck et al.⁹⁶ also demonstrated that higher concentrations of peroxide bleaching agents for even a short duration caused an immediate reduction in bond strength.

Dishman et al.⁹⁷ evaluated the effect that 25-percent hydrogen peroxide had on bond strength immediately after bleaching and at various times after bleaching. Immediately after in-office type bleaching, a significant decrease in bond strength could be seen. Within 24 hours of the bleaching period, the bond strength was similar to that seen when bleaching had not been performed.

Miles et al.⁹⁸ conducted a study to determine if at-home carbamide peroxide bleaching affected the tensile bond strength of a precoated orthodontic bracket; recently bleached teeth had significantly reduced bond strengths compared with teeth not bleached and with teeth bleached one week prior to bond strength testing.

Titely et al.⁹⁹ compared the strength of the adhesive bond between bleached and unbleached bovine enamel and concluded that teeth exposed to 35

percent hydrogen peroxide showed a significant reduction in bond strength.

Murchison et al.¹⁰⁰ evaluated three 10-percent carbamide peroxide home bleaching agents to determine their effect on tensile bond strength and concluded that short-term regimens of 10-percent carbamide peroxide do not significantly affect tensile bond strength.

STORAGE OF SPECIMENS

The Centers for Disease Control and Prevention (CDC, 1988) and the United States Occupational Safety and Health Administration (Dept. of Labor, 1991) dictate that extracted human teeth used in research be treated as potential sources of bloodborne pathogens. It is preferred that extracted teeth intended for research be sterilized prior to use.¹⁰¹ The tooth-storage media utilized for laboratory testing varies from one study to another. Some preservatives include: 70-percent ethyl alcohol, 0.1-percent thymol, formaldehyde, glutaraldehyde, sodium hypochlorite, 10-percent buffered formalin, saline, 0.5-percent chloramine, and deionized water. Some studies do not specify a storage medium while others claim the specimens were stored in various antiseptic solutions. The storage media keep the specimens free from fungal and bacterial contamination and prevent dessication. It is believed by some researchers that the storage media can have an effect on the properties of the teeth and their bond strengths. Shaffer et al.¹⁰² evaluated the effect of glutaraldehyde, sodium hypochlorite, and autoclaving on the shear bond strength of composite cylinders bonded to enamel surfaces and noted no significant change in surface morphology or bond strength. Pashley et al.¹⁰³ found no change in the intrinsic permeability of the dentine or shear bond strength in specimens sterilized by autoclaving or ethylene oxide gas. Kimura et al.¹⁰⁴ reported that human third

molars stored for six months in 10-percent formalin before they were surfaced showed a doubling of bond strength compared with teeth stored in 4 °C physiologic saline. In contrast, Mitchem and Gronas¹⁰⁵ found that composite-tooth shear bond strength was not altered when teeth were first stored in 10-percent formalin and then transferred to water. Formaldehyde readily oxidizes in air and forms acid, altering the pH of the storage media. Oen et al.¹⁰⁶ reported that buffered formalin is a suitable storage medium for extracted teeth. It has been suggested by Causton and Johnson¹⁰⁷ that the ionic content of the storage solution could have an effect on bond strength of polycarboxylates to dentin. The Accredited Standards Committee task group concluded that storage media and duration of storage do not significantly affect enamel or bond strength.¹⁰⁸

THERMOCYCLING

Thermocycling is a laboratory method used to simulate and accelerate the aging process of materials. This procedure is widely used in bonding studies and is accomplished by subjecting specimens to thermally controlled streams of water ranging from 4 to 6 °C. Various studies indicate the widespread use of thermocycling. However, there is to be a lack of uniform thermocycling times and temperatures. In 1990 the Council on Materials, Instruments, and Equipment of the American Dental Association proposed guidelines for testing of dentine adhesives that included 4000 cycles of thermocycling.¹⁰⁹

Burger et al.¹⁰⁹ compared the effect of five thermocycling cycles (100, 500, 1000, 2000, and 4000) on the shear bond strength of composite resin to dentine and found no significant difference among the thermocycled groups.

Carracho et al.¹¹⁰ evaluated the time of storage and thermocycling on the shear bond strength of three dentinal adhesives and concluded that thermocycling

significantly reduced the shear bond strength of two adhesives. Bishara et al.¹¹¹ evaluated the shear bond strength of orthodontic resins that were subjected to severe temperature changes and noted a corresponding decrease in the shear strength of the adhesive. Klockowski¹¹² evaluated the shear bond strength of four orthodontic adhesives and noted a decrease in bond strength due to thermocycling.

TEST METHODS

A significant number of studies have addressed the *in vitro* bond strengths of orthodontic brackets attached to tooth structure. Six types of adhesion tests are often utilized: lap shear, cleavage, tensile, torque, bending and peel. According to Retief, a subcommittee on Standard Test Methods for Direct Filling Materials, Dental Materials Group of the I.A.D.R., decided in 1967 that a tensile test is the preferred method to express the tensile adhesive-enamel bond strength.¹¹³ In order to adequately evaluate a bond, Beech et al.¹¹⁴ in 1980 proposed evaluating shear bond strength as well as tensile bond strength. It was proposed that with a tensile test alone, force was transmitted through the body of the adhesive, and that a partial cohesive failure, rather than an interfacial failure, occurred. In a 1992 symposium on adhesion to restorative materials and tooth structure, no technique was found to adequately quantify the oral adhesive bond. Due to this testing limitation and a desire to understand the loads required for bond failure, an emphasis on fracture mechanics principles that derive from finite element modeling has been observed.¹¹⁵

Many *in vitro* tests are conducted with the intention of gaining clinically significant information. At the present time, there is no consensus about which test most realistically duplicates the clinical situation, or which *in vitro* bond strength is necessary to predict clinical success.

The nominal bond strength, or stress at failure between the adhesive and the substrate, is usually reported as the load at failure divided by the cross-sectional area of the bonded surface. Conventional tests of bond strength have tested this nominal stress at failure. Because there are uncontrolled variables, it is often difficult to compare results of one study with another. There is a need for the development of a standard test of bond strength to allow a more realistic comparison of the data obtained from different tests. Various studies have identified areas of weakness in the current test methods that are used to determine nominal stress at failure.^{116,117}

Van Noort et al.¹¹⁶ tested the sensitivity of bond strengths to changes in testing conditions by using finite element stress analysis. The nominal bond strength could change with specimen geometry, loading configurations or material stiffnesses, because different stress distributions arise.

Katona and Chen¹¹⁷ utilized an engineering model to explain the variations found in load alignment on the tensile bond strength of bonded brackets. Test specimens need to be well aligned, but load bracket misalignment is practically unavoidable, the study found.

Katona and Moore¹¹⁵ used a finite element model of an orthodontic bracket bonded to enamel to determine the effect of load misalignment on the calculated stresses within the cement layer. Tensile load misalignment resulted in an increase in the calculated peak stresses. A 1 N force applied uniformly to the bracket generates less stress within the cement than a 1 N force applied unevenly.

In the clinical setting, bonded attachments are likely to be subjected to uneven shear and torque forces. Other variations seen clinically are moisture control, specimen preparation, and oral temperature fluctuations.

In designing an *in vitro* study to analyze dental materials, standardization of technique is essential. Data collected using standardized experimental methods are more accurate, reproducible, and comparable.

FAILURE SITE

SEM analysis after bracket failure allows for inspection of failure type. The site of bond failure gives information about the quality of the bond between the adhesive and bracket and the tooth and the adhesive. A cohesive failure occurs between two like materials which can be comprised of the bonding medium, the tooth surface, or plastic brackets. An adhesive failure can occur between two unlike materials such as the enamel and the adhesive or the base and the adhesive interface. An adhesive failure indicates the wetting properties or chemical reaction with the substrate could have limited the joint strength. Clinically it is preferred that the failure mode be an adhesive failure at the enamel-adhesive interface. This type of failure leaves less adhesive on the tooth and makes tooth clean-up easier. This failure mode, however, could also subject the tooth to enamel fracture, which is clinically unacceptable. *In vitro* bond testing of direct-bonding systems has shown that stainless steel brackets commonly fail at the adhesive-bracket interface.¹¹⁸

ADHESIVE REMNANT INDEX

The Adhesive Remnant Index (ARI) of Artun and Bergland¹¹⁹ is a four-point scale to quantify the amount of adhesive left on the tooth after debonding. The smaller the ARI number, the less adhesive left on the enamel surface. The scale is broken down as follows:

- 0 = No adhesive left on the tooth.
- 1 = Less than half of the adhesive remaining.
- 2 = More than half of the adhesive remaining.
- 3 = All of the adhesive remaining, showing the impression of the bracket base.

Carstensen¹²⁰ evaluated the clinical effectiveness of a 2-percent versus a 37-percent phosphoric acid etch prior to bonding. No statistically significant difference was found between the failure rates of the two etching procedures. Debonding of the brackets from surfaces etched with 37-percent acid commonly resulted in considerable amounts of adhesive left on the teeth. Debonding of brackets from the 2-percent group, however, resulted in ARI scores of 1 or 0, indicating little or no adhesive remaining on the teeth. Etching with the lower acid concentration reduced the total loss of superficial enamel and reduced the depth of acid penetration into the deep enamel layer without clinical limitations in bond strength.

In a clinical trial, Kinch, Warltier and Newcombe¹²¹ compared bond failure when a 15-second or 60-second acid etch time was used. No significant difference in failure rate, bond survival time, or cement remaining after debonding was found between the two groups. There was, however, a statistical difference in the ARI according to tooth position within the arch. More cement was left on the incisors and canines than on the premolars. It was concluded that when bond failure occurs on incisors and canines, it does so generally at the composite-bracket interface. In contrast, when failure occurs on premolars, it occurs mainly at the enamel-composite interface.

In a follow-up study, Kinch, Warltier, and Newcombe¹²² compared two methods of debonding and the effect the methods had on the amount of adhesive

remaining on the tooth. This study found a statistically significant association among the position of the tooth in the arch, bracket type, debonding method and operator. In the maxillary arch, a pattern of high ARI values was found for the incisors with progressively decreasing values posteriorly. Lock-mesh brackets were found to leave more adhesive than the Dynalok or Photo-etch brackets. Bracket removal with a peel force left considerably more adhesive on the tooth. Operator variability was significant in this study. The operator's debonding technique was responsible for the variation in the ARI results. This variation, however, is commonly seen in the clinical practice of orthodontics.

Bennett et al.¹²³ and Oliver¹²⁴ evaluated different methods of bracket debonding for surface changes and residual adhesive after debonding. The method of bracket removal influenced the quantity of residual composite left on the tooth and surface morphology of the debonded surface.

Many aspects of orthodontic bonding have been investigated to increase clinical effectiveness. The present study evaluates mechanical pretreatment with PREMA microabrasion compound to provide the clinician with information regarding the tensile bond strength of brackets bonded to microabraded teeth.

METHODS AND MATERIALS

Sixty intact, noncarious, extracted human mandibular and maxillary bicuspid teeth were selected for the test. All teeth were collected and randomly divided into three groups of 20 and stored in a 3-percent buffered formalin solution.

All specimens were prepared as follows: the crowns of the teeth were sectioned from their roots utilizing a diamond disk. A small piece of modeling dough was pressed on the buccal surface of each crown and the dough-covered facial surface placed on a glass slab. A metal ring 2 cm in height and diameter was placed around the crown. Tray acrylic was thoroughly mixed and poured into the metal ring. Prior to complete tray acrylic polymerization the metal ring was removed and the specimen placed in cold water to prevent excessive heating of the tooth. Once the specimen was cooled, it was thoroughly cleaned with a toothbrush and water to remove any excess modeling dough. After cleaning, a 15-degree bevel was placed at the tooth end of the specimen by using a lathe (Figure 1) to facilitate a secure fit in the stress-breaking debond apparatus.

After beveling, the specimens were stored in distilled water prior to bracket bonding with 3M Unitek Mini Twin adhesive coated metal brackets (3M/Unitek Co., Monrovia, Calif.). These precoated brackets have a base surface area of 0.128 inch² and were chosen to help standardize the bonding procedure.

Group I (Control): The prepared specimens were rinsed for 20 seconds using an air-water syringe, cleaned using a slurry of nonfluoridated flour of pumice for 30 seconds, rinsed again for 20 seconds, and then dried with oil-free compressed air for 20 seconds. An etching solution of 37-percent phosphoric acid liquid was applied to the enamel surface and allowed to remain for 30

seconds. The etchant was rinsed with tap water for 60 seconds and the tooth surface dried with oil-free compressed air until a chalky appearance persisted.

Primer was applied to the buccal surface of the tooth using a unit-of-use primerswab. Following the application of the primer, the precoated bracket was carefully seated on the mid-buccal surface of the crown with firm seating pressure until the bracket made contact with the tooth. Excess bonding material was removed from around the bracket base with the aid of an explorer. The precoated bracket was then cured for 60 seconds using an Ortholux (Unitek/3M Co., Monrovia, Calif.) visible light (470 nm) curing unit. Curing took place by directing the light source directly at the bracket at a distance of approximately 2 mm (Figure 2).

For 14 days after bonding, the 20 specimens were immersed in a container of distilled water and stored in an incubator set at 37 °C. During that time, the specimens were thermocycled in an automatic apparatus designed by the Indiana University School of Dentistry Department of Dental Materials. The specimens were immersed in water baths of 5 °C and 45 °C, 30 seconds in each bath, for a total of 2,500 cycles. After thermocycling, the specimens were stored in a 37 °C incubator for one week and then tested for tensile bond strength.

The Instron testing machine (Instron Corp., Canton, Mass.) was used to determine the tensile bond strength of each specimen. A stress-breaking apparatus (Figure 3) was utilized to support and align the specimen in the upper member of the Instron machine. The specimen was placed in the apparatus with the bracket facing the lower member of the Instron. A fishing line was used to securely engage the bracket wings of the specimens without producing undue stress to the bonded bracket. The free end of the fishing line was held around the hook secured to the lower member of the Instron testing machine (Figure 4).

A load at a crosshead speed of 0.5 mm per minute was applied until bond failure occurred.

Group II (PREMA): Twenty specimens were prepared for bracket bonding in a similar manner to Group I; however, before acid etching, PREMA compound was applied to the buccal surface of each specimen. A small amount of PREMA compound was placed on a disposable mandrel tip on a low speed 10:1 reduction contra angle. The material was compressed onto the buccal surface of the specimen for 20 seconds and then rinsed with tap water for 30 seconds. The procedure was repeated 10 times followed by drying the specimens with oil-free compressed air. All 20 specimens were then treated in the same manner as Group I starting with the 37-percent phosphoric acid etch.

Group III (PREMA + 6 weeks): This group of 20 specimens was treated in a similar fashion to Group II; however, after the PREMA compound application and prior to etching, the specimens were placed in distilled water at 37 °C for six weeks.

After debonding the brackets were examined visually and with the aid of a light microscope to determine the site of bone failure. Failures were classified as adhesive or cohesive in nature. Adhesive failures were those occurring between the adhesive and enamel or the adhesive and bracket. Cohesive failures were those occurring within the tooth structure. An adhesive remnant index number from 0 to 3 was assigned to each specimen.

The data were statistically analyzed using one-way analysis of variance at the 0.05 level.

RESULTS

TENSILE BOND STRENGTH

Mean bond strengths were calculated and analyzed for significant differences using one-way analysis of variance. The mean bond strength with standard deviation for each of the three test groups is shown in Table I and graphically represented in Figure 5. Technical problems occurred with two samples from Group III spontaneously debonding prior to testing and one sample in each of the three groups exhibiting enamel fracture on debond. Statistical analysis was done including and excluding these problems, and no significant difference in the mean bond strength within groups was recorded. The mean bond strength of Group I with spontaneous debonds and enamel fractures excluded (12.20 MPa) was numerically lower than Group II (12.73 MPa) and Group III (13.68 MPa). A statistically significant difference in mean bond strength was not obtained. A power analysis of the statistical test was performed.

BOND FAILURE SITE

The sites of bond failure, determined by visual exam with the aid of a light microscope, were mainly adhesive at the bracket-adhesive interface. This corresponded to an Adhesive Remnant Index score of 3. An ARI of 3 represents all of the adhesive remaining on the tooth surface, showing the impression of the bracket base (Figure 6).

FIGURES AND TABLES

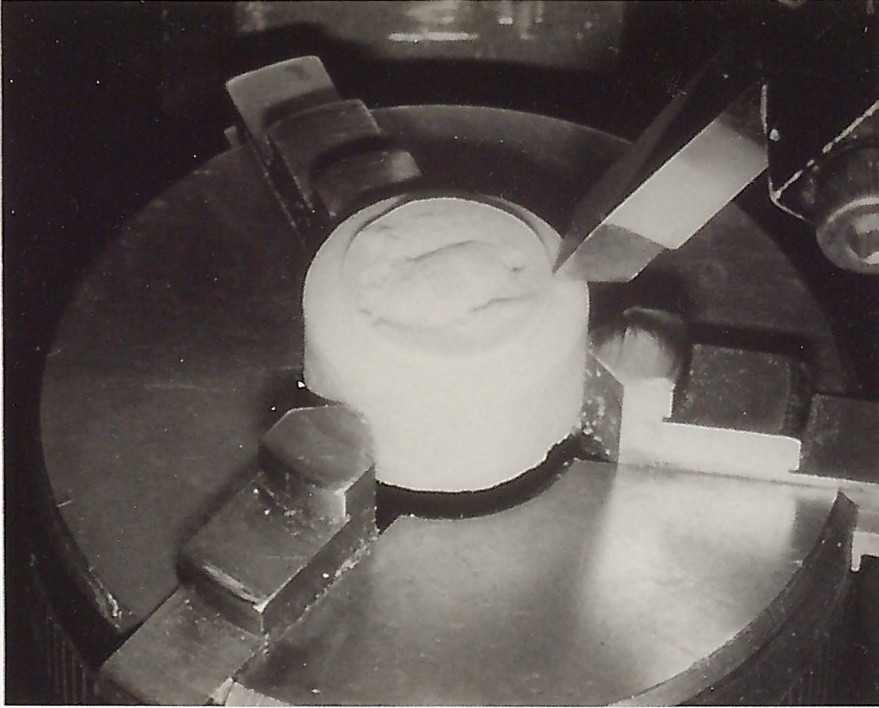


FIGURE 1. Specimen in lathe.

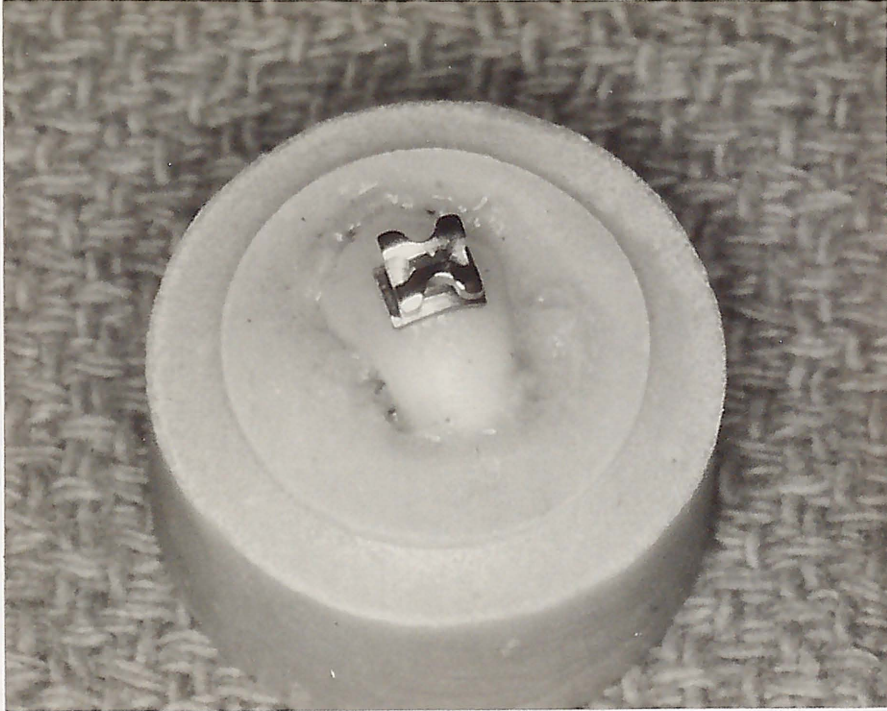


FIGURE 2. Specimen with bracket bonded to enamel surface.

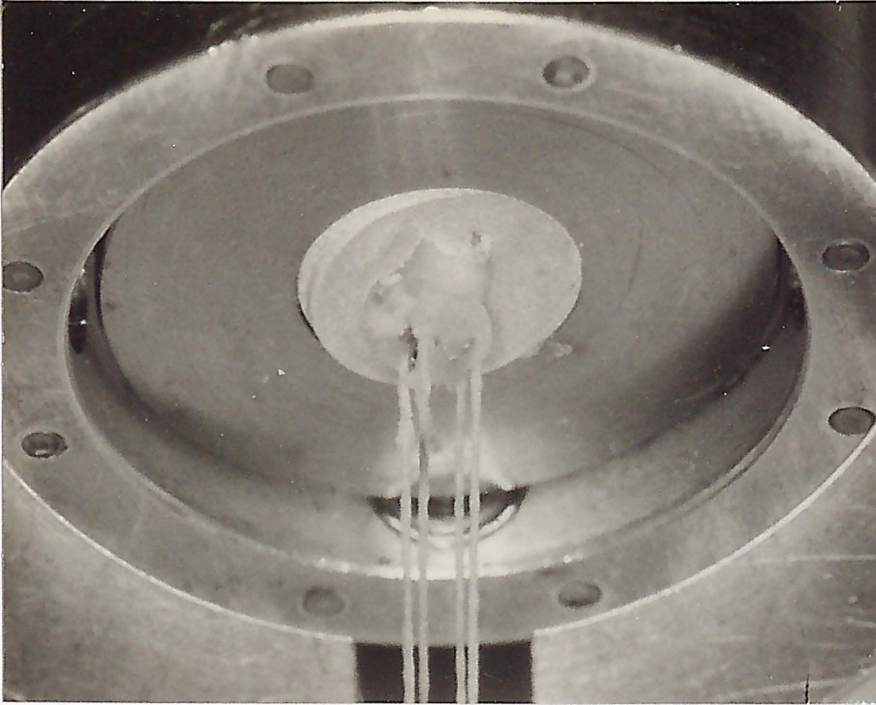


FIGURE 3. Stress-breaking apparatus to support specimen.

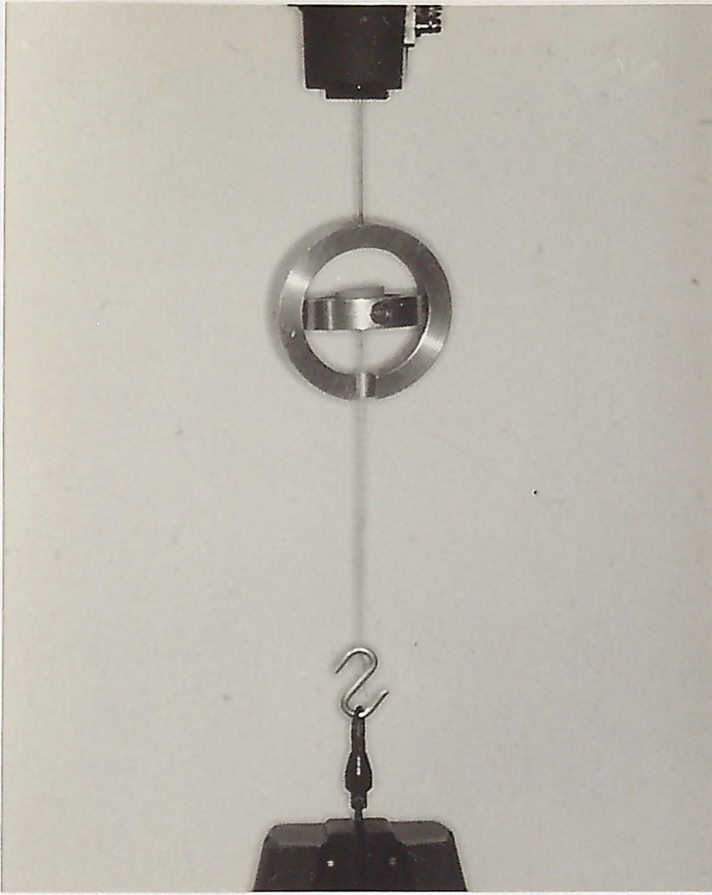


FIGURE 4. Specimen in the Instron testing machine.

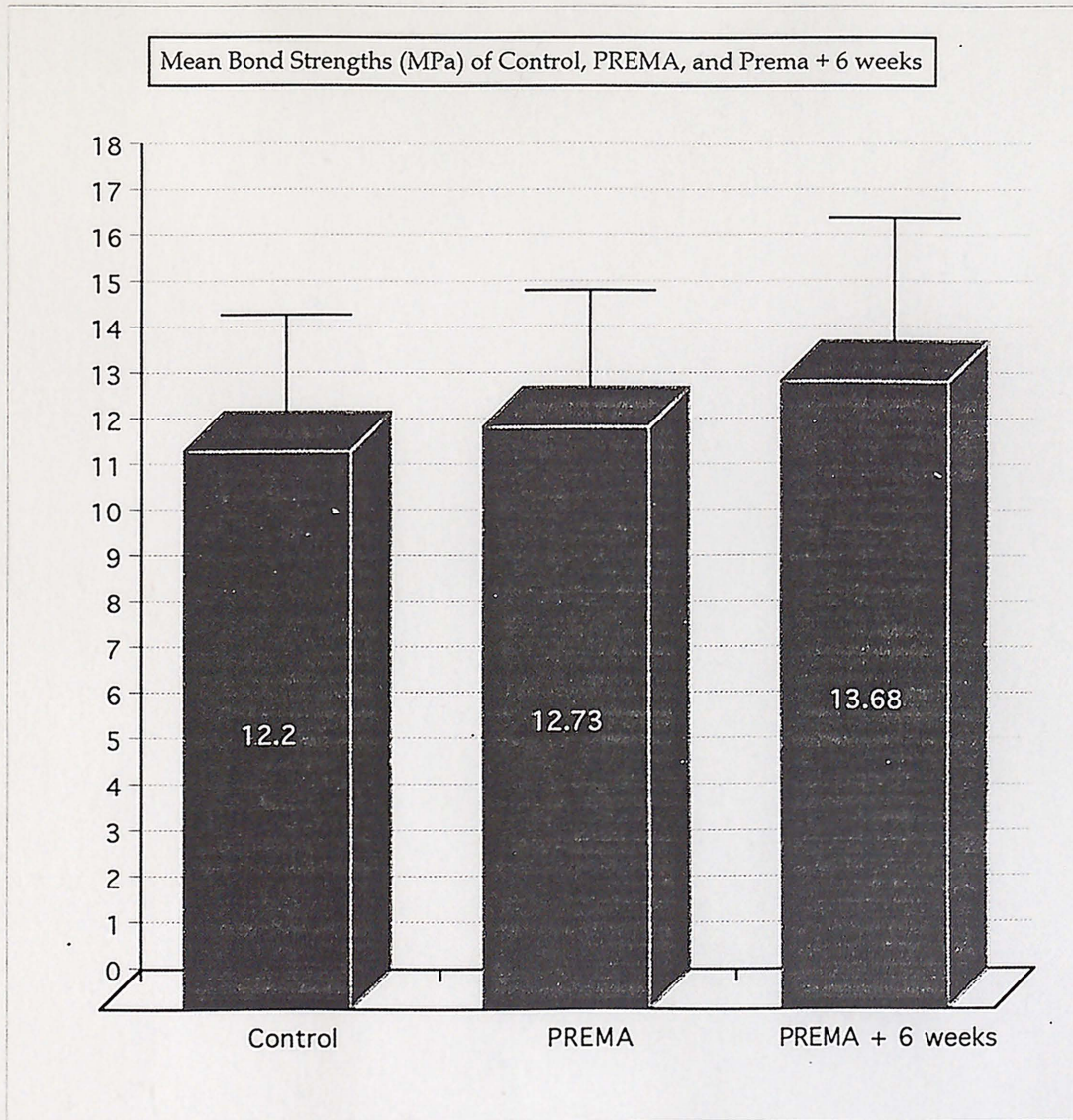


FIGURE 5. Data from Table III. (Spontaneous debonds and enamel fractures excluded.)

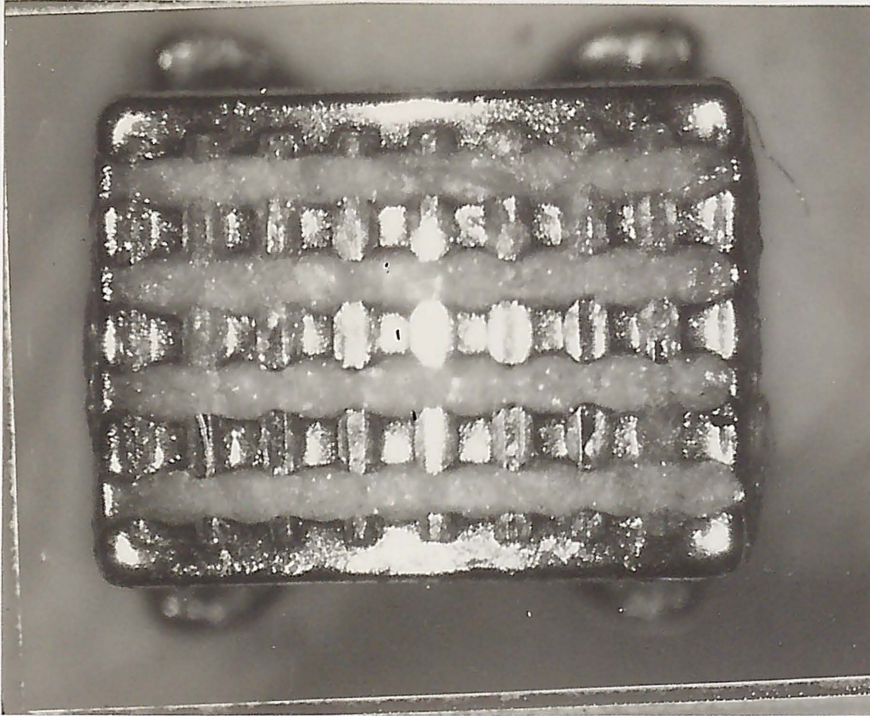


FIGURE 6. SEM (X20) bracket-adhesive interface bond failure.

TABLE I

Tensile bond strengths*

GROUP	NUMBER	MEAN (MPa)	STANDARD DEVIATION
I. Control	19	12.2	2.48
II. PREMA	19	12.73	2.34
III. PREMA + 6 Wks	17	13.68	2.88

*Spontaneous debonds and enamel fractures excluded.

DISCUSSION

Enamel fluorosis has become more prevalent and widespread. The increased incidence may be due to a rise in the amount of fluoride ingested by patients since birth. Vehicles of ingested fluoride include: water supplies, dentifrices, vitamins, food, and professional dental fluoride treatments. Enamel staining has accompanied this increase in fluoride with an associated increase in the number of patients seeking removal of the stains. Several techniques, including sandpaper disking, hydrochloric acid abrasion, 12-fluted bur mechanical treatment, PREMA compound abrasion, peroxide bleaching, and combinations thereof have been used to remove intrinsic stains.

This *in vitro* bond strength study was designed to simulate clinical bonding procedures; however, compromising situations such as saliva contamination, lack of visual access and patient compliance were not considered. Adhesive precoated brackets were selected to reduce adhesive variables. A 37-percent acid etchant concentration was selected because of its wide clinical use in orthodontic bonding. Thermocycling of all specimens was conducted to attempt to reproduce the effects of the oral environment.

The effects of microabrasion have been evaluated in studies using SEM. The treated enamel is removed by chemical erosion and mechanical abrasion. Uniform enamel removal in the range of 50 to 150 μm has been reported.⁹¹ Microabrasion creates a smooth polished layer by deposition and compaction of calcium and phosphate breakdown products that result from the simultaneous erosive and abrasive action of the microabrasion compound.⁹¹

Croll and Bullock¹²⁵ state that when bonding to a microabraded tooth surface, the clinician should etch 30 to 45 seconds longer than usual. With tensile

bond strength as the measure, our results do not indicate a need to etch microabraded teeth longer prior to orthodontic bracket bonding. The results of this study indicate that teeth etched in the usual manner using 37-percent phosphoric acid, those with PREMA microabrasion immediately prior to bonding, and those microabraded with PREMA compound and immersed in distilled water for incubation storage for six weeks prior to bonding, showed no significant difference in tensile bond strength.

This study, however, used healthy extracted human premolars, and no attempt was made to use teeth with enamel fluorosis. Ng'ang'a et al.³⁹ compared *in vitro* the tensile bond strength and bond failure site of brackets bonded to fluorotic and nonfluorotic teeth and concluded that the difference between the means for bond strength were not statistically significant. It has been suggested that enamel with a high fluoride content is more resistant to acid etching and consequently could result in poor retention of orthodontic brackets.⁴⁰ Opinya et al.⁴⁰ evaluated the tensile bond strength of fluorosed Kenyan teeth and concluded that grinding the enamel prior to acid etching resulted in an increase in tensile bond strength. Brannstrom et al.¹³ evaluated the appearance of etched enamel after mechanical pretreatment with a diamond point or aluminum oxide disc and found no significant difference in the appearance of the etched enamel surface. The team also evaluated a fluoride varnish applied to the enamel to increase the fluoride content and found the varnish had no negative effect on the etching results. Contradictions in these study results could stem from factors such as: difference in the enamel concentration of fluoride, type and concentration of acid etchant, length of acid etching, and criteria to evaluate resistance to etching. Further clinical and experimental data are necessary to obtain a general consensus on the influence that fluorosis has on enamel bonding.

Site of bond failure, as determined by visual examination with the aid of a light microscope, was generally found to be at the bracket-resin interface, where there was a large amount of adhesive left on the enamel. This type of failure requires time-consuming cleanup. One specimen in each of the three groups exhibited enamel fracture at debond. This occurrence was consistent throughout the three groups and suggested that there could have been undetected enamel irregularities in the specimens. Two specimens in Group III spontaneously debonded prior to placement in the Instron machine. Failure was at the tooth-resin interface and demonstrated that the tooth-resin interface was the weak link. These specimens were included in one statistical analysis and omitted in another without any effect on the results. Mean bond strengths were 12.2 MPa to 13.7 MPa, with the specimens receiving microabrasion demonstrating insignificantly higher bond strengths. A power analysis of the statistical test was performed. The power of the performed test (0.1085) was below the desired power of 0.8000. The negative findings should be interpreted cautiously. The differences in the mean values are not great enough to exclude the possibility that the difference is due to random sampling variability.

A follow-up study using extracted human fluorotic teeth and a storage medium that allows remineralization could be conducted to enhance our knowledge of the effects PREMA compound has on the tensile bond strength of orthodontic brackets to previously microabraded teeth.

SUMMARY AND CONCLUSIONS

This study evaluated the tensile bond strength of stainless steel orthodontic brackets bonded to previously microabraded teeth. Sixty extracted human premolars were divided into three groups of 20 specimens. Groups with bonding immediately after PREMA microabrasion, six weeks after PREMA microabrasion, and a control group with no microabrasion were compared. All specimens were thermocycled to simulate the oral environment and tested to failure in tension using an Instron testing machine. Specimens were then examined with the aid of light microscopy to determine the site of bond failure.

The results showed that teeth etched in the usual manner using 37-percent phosphoric acid, those with PREMA microabrasion immediately prior to bonding, and those microabraded and stored for six weeks prior to bonding showed no significant difference in tensile bond strength. Bond failure in the three groups occurred predominately at the resin-bracket interface.

The results of this study indicate that tensile bond strength is not significantly affected by PREMA microabrasion, and indicate that it is not necessary to postpone enamel microabrasion prior to orthodontic bracket placement. This study also indicates that it could not be necessary to increase the etching time for teeth previously microabraded with PREMA compound. The results support the null hypothesis.

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ABSTRACT

TENSILE BOND STRENGTH OF STAINLESS STEEL
ORTHODONTIC BRACKETS ON
MICROABRADED TEETH

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Microabrasion with PREMA Compound (Premier Dental Product Co., King of Prussia, Penn.) has been advocated for the removal of superficial enamel stains. This procedure eliminates stains by removing a microscopic layer of enamel. The objective of this study was to determine whether the use of PREMA microabrasion prior to orthodontic bonding affects the tensile bond strength of an adhesive precoated stainless steel orthodontic bracket. Sixty noncarious extracted human premolar teeth were randomly divided into three groups of 20 and stored in 3-percent buffered formalin solution. Group I was a control group that was etched and bonded in the usual manner. Group II received PREMA Compound microabrasion immediately prior to bonding. Group III received PREMA microabrasion followed by a six-week storage period prior to bonding. After bonding, specimens were thermocycled and stored in distilled water at 37 °C for 14 days. The specimens were then loaded to failure in the tensile mode

of an Instron testing machine (Instron Corp., Canton, Mass.). A stress-breaking apparatus was utilized to minimize all forces other than tensile. The data was statistically analyzed using one-way analysis of variance at the 0.05 level. No statistically significant differences were found among the three groups. From these results it was concluded that microabrasion with PREMA did not affect bond strength. Enamel microabrasion can be provided prior to orthodontic treatment without any detriment to bracket bond strength.

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